An Ocean-Altimetry Measurement Using Reflected GPS Signals Observed from a Low-Altitude Aircraft

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Abstract—**We present the first ocean-altimetry measurement made using reflected GPS signals. Data were collected from a Cessna airplane flying off the coast of Santa Barbara, California, where the direct and ocean-reflected GPS L1 signals were recorded onboard at 20.456 MHz. In addition, the direct signals were processed with a TurboRogue receiver and used to derive accurate receiver positioning. The high data rate samples were processed with a "software GPS receiver", developed for this task, to extract the direct and reflected signal waveforms, using both the C/A and Y-codes. These waveforms were fit to obtain a direct/reflected reception delay each second. These delays were then fit for ocean height and clock offset. Preliminary results for the C/A-code waveforms show the mean of the measured 1-sec values agrees well with altimetry database values, and the residual height RMS during straight, level flight is 3.1 m, and for all data and all PRNs, is about 4.6 m. Further analysis refinements, including more accurate waveform modeling and fitting, C/A-code sidelobe elimination, atmospheric modeling, and the use of Y-code waveforms, will likely improve these results.**

INTRODUCTION

Current-generation orbiting altimeters, such as Topex/Poseidon (T/P), Jason and ERS, have greatly improved our understanding of Earth's climate. Unfortunately, the study of ocean eddies requires spatial and temporal resolutions finer than that offered by these systems, and have not yet been observed globally. The possibility of using reflected GPS signals for remote sensing has been proposed [1], and studied specifically for altimetry [2]. A lack of capable instruments has prevented studying GPS-reflections from spaceborne platforms, and to-date, only one space-based GPS reflection has been observed [3]. An alternative approach to understanding space-based GPS altimetry is to make measurements from lower-altitude platforms, where more experimental control and larger data sets can be obtained, and scale the results to low-Earth orbit. The experiment described here is a first attempt in this program.

EXPERIMENTAL SETUP

The overall experiment consisted of a Cessna airplane flying over a variety of terrain, while an onboard data acquisition system recorded the received GPS signals. The data used in this experiment was limited to that recorded over the Pacific Ocean, off the coast of Santa Barbara, California, at an altitude of about 1.5 km and velocity of 50 m/sec. The flight path began with a 3 km-diameter circle, followed by approximately straight and level flight. Direct GPS signals, received from an omni-directional RCP antenna, located on top of the aircraft, were combined with reflected signals received using a 12 dB LCP helibowl antenna pointing approximately 30° below the horizon, at right angles to the flight path. Figure 1 shows the data acquisition system. A TurboRogue GPS receiver locked onto the direct signals to calculate accurate receiver positions that were recorded onto internal flashcard memory. The TurboRogue was modified so that the internal, digitized, L1-I/Q and L2-I/Q signals passing from its front-end to its processing unit were tapped for recording. A Sony SIR-1000, clocked with the TurboRogue's internal 20.456 MHz signal, recorded the L1-I signal onto tape media continuously for the 1.5-hour flight.

DATA PROCESSING

The 20.456 MHz, single-bit sampled, L1-I data were processed with software developed for GPS altimetry that performs many functions of a delay/Doppler-mapping GPS receiver. The software cross-correlated all PRN/Doppler values and noted all GPS detections, found the 50-Hz navigation-bit boundaries, decoded these bits to obtain accurate timing information, and initiated a phase and delay-locked loop to track the direct GPS signal, for each PRN detected. Inside this tracking loop, the C/A or Y-code waveforms were calculated by cross-correlating the tracking model with the data and accumulating for the desired integration time, 10 msec in this case, and saved to disk.

The 10 msec waveform amplitudes are incoherently integrated into 1-sec waveforms and normalized to form voltage SNR. Figure 2 shows and example 1-sec waveform. Both the direct and reflected waveforms were fit using expected model shapes, parameterized with an amplitude and reception-time variable. The difference between the reflected and direct-signal reception-time parameters is our primary observable: measured 1-sec delay differences. Using accurate satellite positions, reprocessed TurboRogue receiver positions, and the WGS 84 Earth model, we estimate the 1-sec delay differences and subtract from the measured values. The resulting residuals were fit with two parameters: a clock-offset parameter, and an ocean height offset parameter.

RESULTS AND CONCLUSIONS

The best-fit clock error was 5.3 nsec, consistent with cabling and other instrumental delays, and possible fitting biases. The best-fit ocean height-error parameter was –37.1 m, which compares reasonably well with an altimetry database value of –35.7 m, given this region is topographically complex and far from a T/P track. Figure 3 shows the post-fit residuals for the 7 PRNs detected. Note that flying in a circle in order to detect a large number of different satellites was necessary to separate uncalibrated clock-like effects from ocean height. On the other hand, Figure 3 points to the presence of systematic errors associated with PRN number, and the ongoing analysis is currently focused on their origin. The RMS is 4.6 m for all points, and 3.1 m for the straight-path segment (points after 300 seconds in Figure 3) which might better represent the altimetric accuracy of these data, assuming the gross PRN effects can be eliminated. These will likely improve with better waveform modeling, estimating atmospheric effects, eliminating C/A-code sidelobes which appear to bias the fits, or using the Y-code waveforms just currently available.

REFERENCES

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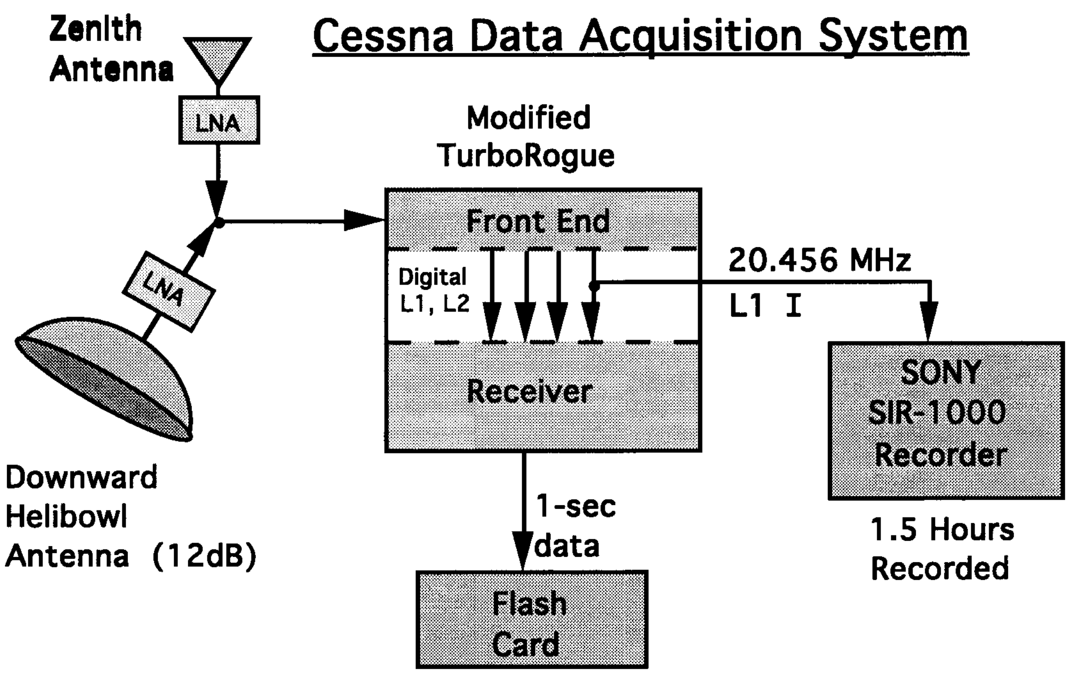

Figure 1

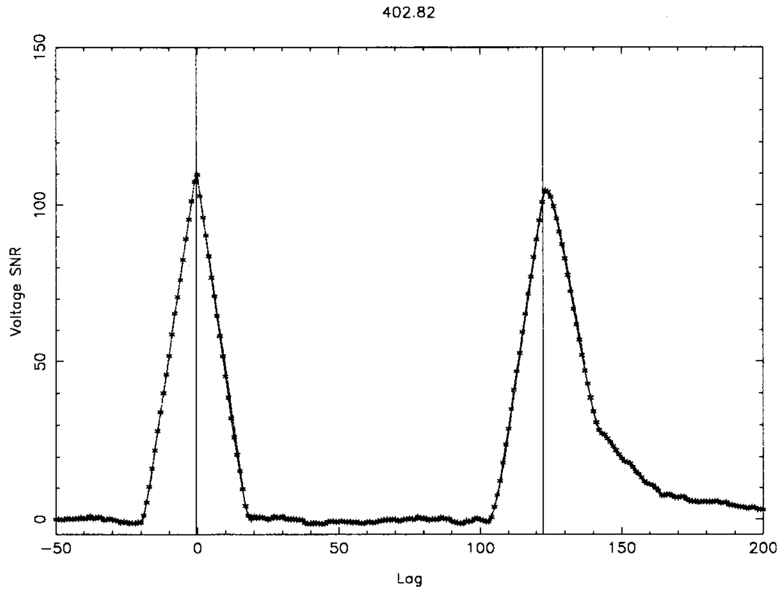

Figure 2. Typical 1-sec waveform showing voltage SNR as a function a lag (48.9 nsec samples). The peak on the left is the direct, satellite-to-Cessna signal, and the left peak is the ocean-reflected signal. The vertical lines show the best fit to the direct and specular reception, respectively (the specular reception is not expected at the peak).

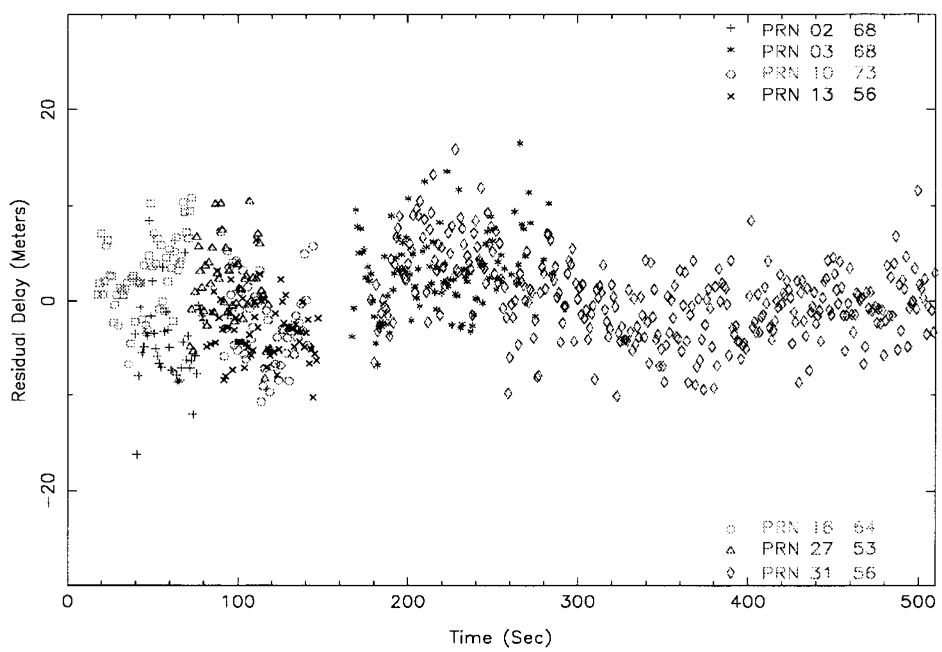

Figure 3. Residual 1-sec height measurements. Several systematic error sources are seen, but the overall RMS is 4.7 m. The RMS of the data after 300 sec is 3.1 m.